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Fabrication and Performance of Separately-Biasable Antiparallel-Pair "T-Anode" Mixer Diodes Employing A Compact Multiple-Layer Integrated Bias Circuit at 210 GHz

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ABSTRACT

A 210 GHz waveguide subharmonically-pumped mixer with integrated antiparallel-pair planar "T-anode" Schottky diodes and a novel compact multiple-layer bias circuit has been successfully fabricated and measured. The diode anodes are defined by electron-beam lithography using technology similar to that employed for T-gate transistors. A compact multiple-layer filter structure provides individual biasing capability for each diode, which reduces the required local oscillator power for subharmonic mixing. Unbiased, a DSB mixer noise temperature of 1420 K was achieved with 6.4 mW of required LO power. Using separate diode bias to reduce the required LO power to 3.2 mW, the noise temperature increased slightly to 1640 K. This is the lowest noise temperature reported for a separately biased mixer at this frequency.

I. INTRODUCTION

Not long after the Sub-Harmonically-Pumped (SHP) antiparallel-pair diode mixer arrangement was first introduced by [1,2], an SHP receiver operating at millimeter-wave frequencies was demonstrated by the Radio Astronomy group at Bell Laboratories [3,4]. These pioneers, together with groups that followed, utilized whisker-contacted diode pairs to provide the anti-symmetric I-V characteristics that are essential to efficient even harmonic mixing. Recent advances in fabrication technology have led the way to a new style of device that is replacing conventional vertical whiskers with horizontal air-bridged metal fingers and planarized diode structures. Thanks to the introduction of the surface channel etch technique [5], that made chip style low-parasitic planar diodes available, planar antiparallel-pair diodes were shown to perform as well as their whisker-contacted counterparts up to 200 GHz [6]. Moreover, a recent subharmonic planar-diode mixer utilizing a new T-gate-like technology to define the anodes, and a novel substrate transfer technique to place active circuit elements on low-loss quartz, has yielded extra low Parasitic devices and record noise performance at 200 GHz [7].

However, the excellent millimeter-wave subharmonic-mixer performance now being realized by several groups comes with a price: much higher required local oscillator power than needed for either fundamental or single-diode harmonic mixing. This is due to the difficulty involved in incorporating individual diode bias circuitry with the antiparallel-pair and is the most limiting factor in scaling SHP mixers up to higher submillimeter-wave frequencies where significant local oscillator power is unavailable.

Prior implementations for adding individual-diode bias to SHP mixers in waveguide-based [8] or MMIC-based circuitry [9] have required fairly large bypass capacitors for DC isolating the two devices. This makes the implementation especially difficult in high-frequency waveguide structures where large open areas are often difficult to implement without engendering mode problems. A very compact bias circuit arrangement was recently demonstrated in an open structure quasi-optical SHP mixer system at 180 GHz [10]. This arrangement utilizes a gap-cap configuration on one side of the two diodes and requires that there be a split in the feed lines going to the devices on this side of the circuit. Such an arrangement is not practical in a waveguide SHP circuit where there is generally not enough space to implement the feed-line gap.

In this paper we describe a very compact multiple-layer bias circuit for an antiparallel-pair-diode arrangement which can be implemented in microstrip or stripline. In addition, we have coupled this bias circuit arrangement with our new T-anode diode process to produce extremely low-parasitic devices which yield very good mixer performance.

II. DEVICE/BIAS CIRCUIT IMPLEMENTATION

The individual-diode bias concept we have realized was first proposed by the millimeter-wave development group at Rutherford Appleton Labs in the U.K. [11]. It can be implemented in microstrip or stripline and uses a multiple-layer conductor/insulator arrangement to isolate the two diodes of the antiparallel pair. The configuration was first tested with optically formed diodes in an existing mixer block at 215 GHz [12].

The device geometry we have employed is an extension of HEMT and FET T-gate technology and results in long thin anode contacts which can be made with ultra-small areas. The advantages over more traditional oxide-patterned anodes lie in no finger-to-anode alignment, reduced spreading resistance, equivalent or reduced parasitic contact-finger capacitance and a more reproducible process. Disadvantages include the need for e-beam direct write of the anodes and fingers and, perhaps, a slightly less robust device (due to), having no oxide around the anode to help hold the metallic contact-finger in place).

The completed circuit structure looks very similar to that described in [6], and consists of a lithographically formed microstrip RF filter circuit on each side of an antiparallel-pair GaAs diode, together on a fused quartz substrate. However, in this instance, the two diodes are DC isolated on one side using a double-layered metallization pattern with nitride forming the insulating barrier. Strong capacitive coupling along the whole length of the two filter layers preserves the AC performance by providing a short circuit at the signal, LO and IF frequencies. At the end of the filter, the two metallic layers split into individual bond pads for bringing in the separate device biasing. On the opposite side, the diodes are connected through a common ground to the mixer block. The arrangement is shown in Figure 1.

The device anodes are nominally 0.25 wide by 4 μm long and are formed using our "T-anode" process [7]. The 'T-anode' process, initially developed for high frequency resonant tunneling diodes [13], uses a trilayer PMMA coating exposed with multiple e-beam scans at different doses. Each of the three PMMA layers has a different composition and molecular weight and, when spun and cured layer by layer, shows no evidence of intermixing. The mushroom shape (or T-shape) of the anode is formed by selectively developing each PMMA layer in three developers. Air-bridged fingers that taper out from the anodes and connect to ohmic pads are formed at the same time as the anodes. The lithography is followed by the corporation of 6000 Å of titanium/platinum/gold to form the Schottky contact

The stacked filters that provide a separate biasing path for each active device are formed from a metal/nitride/metal trilayer. The metal layers are titanium/gold deposited by electron-beam evaporation and have a total thickness of 9000 Å. The intermediate nitride layer is deposited by a plasma enhanced chemical vapor deposition system at 250 C to a thickness of 5000 Å. The nitride layer has to have low pin-hole density and good step coverage. The thickness of nitride determines the coupling capacitance required for proper filter performance. For our particular circuit, 6000 Å of nitride results in approximately 1 ohm impedance at the lowest mixer IF frequency of 1.5 GHz. After the filter metallization, a surface channel etch [5] is performed which isolates the anode and cathode and forms the air-bridge contact fingers as seen in Figure 2. This is followed by a backside process that transfers the devices and filter circuits from the GaAs host wafer to a low-loss quartz substrate. This process [14], deemed Quartz Upside-down Integrated Device (QUID), uses a thermally cured epoxy to bond the semiconductor wafer to the quartz carrier. The GaAs substrate is then etched down to an AlGaAs etch stop layer. In the final processing step the remaining AlGaAs/GaAs is patterned and dry-etched, leaving only the areas that are needed for the ohmic and Schottky contacts

III. MEASUREMENTS

DC characteristics for the best separately-biasable device we have been able to fabricate to-date are given in Table 1. For comparison, the characteristics of our best unbiased T-anode-pair diodes are also shown The diode areas are both about 1.2 μm². The slight asymmetry in the biasable-pair's turn-on knees is readily compensated with the external DC circuitry. The higher diode resistance, saturation current and ideality factor for the biasable pair means there is still room for significant device improvement.

Noise measurements on the device shown in Table 1. were performed at ≈200 GHz using the mixer block shown in Figure 1 The results are presented in Table 2. along with published data from other groups at a similar frequency. The lowest noise temperature obtained with this device was 1420 K DSB with a conversion loss of 7.6 dB and 6.4 mW of LO power with zero bias. When both diodes were biased at around S00 μA, the noise temperature increased slightly to 1640 K DSB with 8.4 dB conversion loss and 3.2 mW of LO power. The slight degradation in noise performance with the 3 dB reduction in LO power is believed to be related to the large leakage current of this particular diode pair but more measurements art required before this can be confirmed.

IV. CONCLUSION

A novel separately-biasable-diode subharmonic mixer using T-anode technology and stacked filter structures has been fabricated and tested at: 200 GHz. Although the performance of the mixer is not as good as that of similar circuits with unbiased T-anode devices, it is better than any reported separately biased mixer at this frequency. Substantial reduction in required LO power is obtained when separate bias is applied, although there is a slight penalty in overall noise performance. Substantial improvement in performance is to be expected with improvements in device DC characteristics.

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REFERENCES

[1] M.V. Schneider and W.W.Snell, Harmonically Pumped Stripline Down-Converter," *IEEE Trans. MTT.*, vol 23 no 5, pp. 271-275, Mar. 1975.

[2] M. Cohn, J.E. Degenford, and B.A. Newman, "Harmonic Mixing with an Antiparallel Diode Pair," *IEEE Trans MTT*, vol. 23, 110.8, pp. 667-673, Aug. 1975.

[3] T.F. McMaster, M.V. Schneider, and W.W. Snell Jr., "Millimeter Wave Receivers with Subharmonic Pump," *IEEE Trans. MTT.*, vol. 24, no. 12, pp. 948-952, Dec. 1976.

[4] E.R. Carlson and M.V. Schneider, "Subharmonically Pumped Millimeter-Wave Receivers," *Digest of the 4th Int Conf. Infrared&Millimeter Waves*, pp.82-83, Dec 1979.

[5] W. Bishop, K, McKinney, R.J. Mattauch, T Crowe and G. Green, "A Novel Whiskerless Diode for Millimeter and Submillimeter Wave Applications," *IEEE MTT S Int Microwave Sym. Digest, pp. 607-610,* June 1987.

[6] P.H. Siegel, RJ. Dengler, I. Mehdi, J.E. Oswald, W Bishop, T. Crowe, and R.J. Mattauch, "Measurements on a 215 GHz Subharmonically Pumped Waveguide Mixer Using Planar Back-to-Back Air-Bridge Schottky Diodes," *IEEE Trans. MTT.*, vol.41, no.]1, pp.1913-1921, Nov. 1993

[7] I. Mehdi, S.C. Martin, RJ. Dengler, RP. Smith and P.H Siegel, "Fabrication and Performance of Planar Schottky Diodes with T-gate-like Anodes in 200 GHz Subharmonically-Pumped Waveguide Mixers," to be published on *IEEE Microwave and Guided Wave Letters*, Jan 1996

[8] J.W. Archer, R.A. Batchelor and C.J. Smith, "Low-Parasitic, Planar Schottky Diodes for Millimeter -Wave Integrated Circuits," *IEEE Trans. MTT.*, vol. 38, no. 1, pp. 1522, Jan 1990,

[9] P.H Siegel, S, Weinreb, S. Duncan, W. Berk, A. Eskandarian, and 1).-M', Tu, "Design and Measurement of a 210 (;11~ Subharmonically Pumped GaAs MMIC Mixer-," *IEEE MTT-S Int. Mic. Sym. Digest,* pp. 603-606, 1992.

[10] T.H Lee, J.R East, C.Y. Chi, G.M. Rebeiz, and G.I. Haddad, "A Novel Biased Anti-Parallel Schottky Diode Structure for Subharmonic Mixing," *IEEE Microwave and (bided Wave Letters,* vol 4, *no.* 10, pp.34 1-343, Oct. 1994.

[11] B. Ellison, B. Maddison, and D. Matheson, private communication.

[12] T.] Lee, I. Mehdi, R.J. Dengler, A. Pease and P.H. Siegel, "A Tri-Layer Filter Structure for Individual Device Biasing of Subharmonically-Pumped Mixers Employing Antiparallel-Pair Diodes," ISDRS Conference, Charlottesville, VA, Dec. 7, 1995,

[13] R E. Muller, S.C. Martin, R.P. Smith, S.A. Allen, M. Reddy, i-1. Bhattacharya, and M.J. W. Rodwell, "Electron Beam Lithography for the Fabrication of Air-Bridged, Submicron Schottky Collectors," *J. Vat. Sci. Technology B,* Vol 12, no. 6, pp. 3668-3672, 1994.

[14] I. Mehdi, M Mazed, R Dengler, A. Pease, M. Natzic, and P.H Siegel, "Planar GaAs Schottky Diodes Integrated with Quartz Substrate Circuitry for Waveguide Subharmonic Mixers at 215 GHz," *IEEE MTT-S ht. Microwave Sym. Digest*, pp. *7'19-782., 1994.*

[15] P.H Siegel, I Mehdi, R Dengler, J. Oswald, A. Pease, T. Crowe, W. Bishop, R Mattauch, S. Weinreb, J. East and T. Lee, "Heterodyne Radiometer Development for the Earth Observing System Microwave Limb Sounder," *SPIE Conference on Infrared and Millimeter-Wave Engineering, #1874,* pp.124-137, Jan 1993.

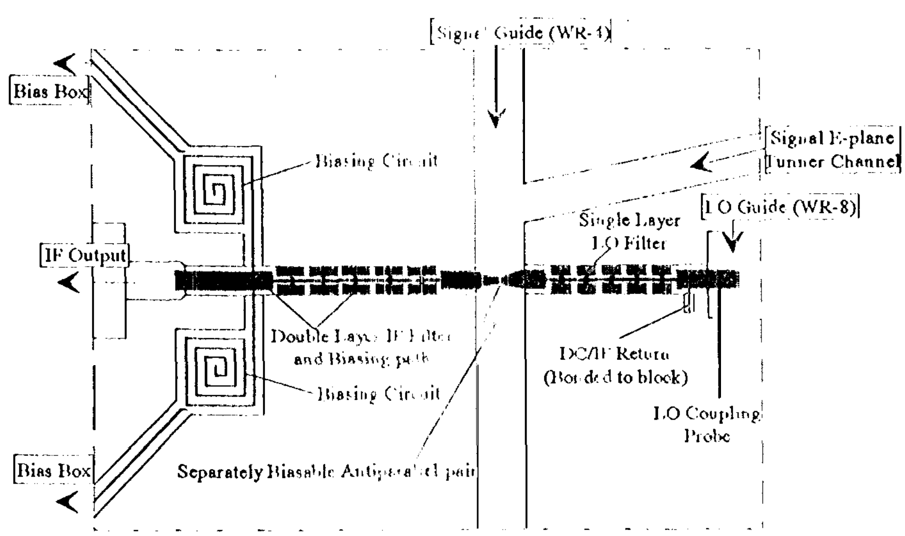

Figure 1. Center portion of the lower half of the mixer split-block that houses biasable diodes and micro-strip circuits.

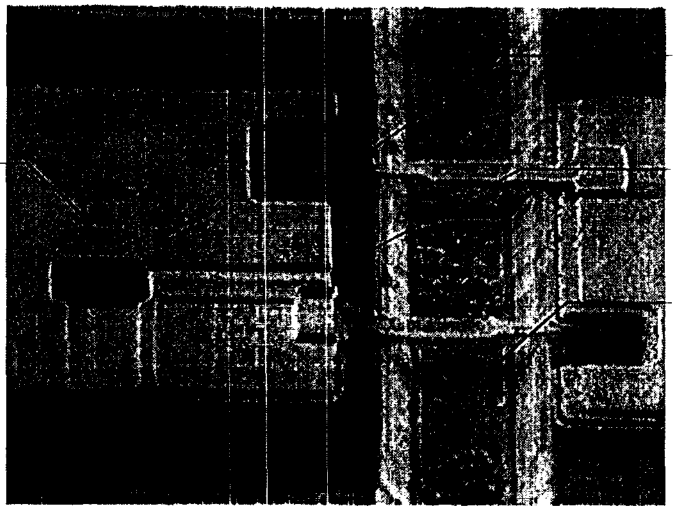

Figure 2, SEM picture of the area surrounding the diode anodes showing multiple-layer bias scheme.

Parameters	R_s (Ω)	η	I_s (A)	V @ 10 µA
Diode 1[1]	13	1.3	3.5×10^{-13}	0.586
Diode 2[1]	16	1.3	5.7×10^{-13}	0.588
Best Diode made using same technology[2]	9.7	1.16	6.8×10^{-16}	0.692

[1] Diode 1 & 2 were fabricated on a 4 x 1017 cm^{-3} epilayer with 2 µm^2 area per anode.
[2] This device was fabricated on a 2 x 1017 cm^{-3} epilayer with 1 µm^2 area per anode.

Table 1. Measured DC parameters of the antiparallel diode whose performance is presented in this paper and the best comparable unbiased device made with similar anode geometry.

Separately Biasable Subharmonic Mixer Configuration	Area per Anode (µm^2)	Bias Condition	LO Power Required	DSB Noise Temperature (K)	Frequency
MMIC chip [15]	3.1	no bias	8.0 mW	2025	200 GHz
		± 500 µA	3.0 mW	2600	205 GHz
Quasi-optical system [10]	1.1	no bias	9 mW	1800	182 GHz
		± 400 µA	4.5 mW	1850	
Waveguide microstrip[1] [17]	3.1	no bias	16 mW	2380	195 GHz
		± 800 µA	8 mW	2730	
Waveguide microstrip[2]	1,2	no bias	6.4 mW	14?0	2.10 GHz
		± 500 µA	3.? mW	1640	

[1] Optically formed anodes with 2pm diameter
[2] This work,

Table 2. Recently published data from separately biasable subharmonic mixers around 200 GHz.